The Construction of a Bioeconomic Model of the Indonesian Flying Fish Fishery

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Abstract The high price of flying fish eggs in Japan encourages South Sulawesi fishermen in Indonesia to harvest increasing quantities of eggs every year. Similarly, the increasing local demand for flying fish encourages Indonesian fishermen to use gill nets to catch more fish. As a consequence of this increasing quantity of eggs harvested and fish caught, Indonesia has become concerned about the overexploitation of the flying fish population.

Thus far policy suggestions concerning the management of the flying fish fishery have been based on a static biological model, since the data needed to construct a dynamic bioeconomic model are very limited. This paper presents a method for constructing a dynamic bioeconomic model of the Indonesian flying fish fishery with very limited data on the fish population. A calibration technique is developed to build the dynamic biological model.

Key words bioeconomics, dynamic optimization, fishery management, resource economics.

Introduction

For the people living on the south coast of Sulawesi (Celebes) in Indonesia, the flying fish and their eggs have been a delicacy for many years. Until the early 1970s, fishermen only caught this fish by using a small-scale fishing technique known as the pakkaja. Pakkajas are barrel-shaped baskets made of slender lengths of split bamboo tied together with twine woven from sugar palm leaves.

In 1968, the Japanese market for flying fish eggs was developed. From 1971 to 1981, egg exports to Japan increased annually at an average rate of 30%. (South Sulawesi Fishery Agency 1990). Paralleling this increase, the local price of flying fish eggs per kilogram increased substantially. Zerner (1987) noted that the price of eggs per kilogram was approximately $2.41 in 1971, increasing to $10.50 in 1985. In contrast, the local price of the fish was $0.20 per kilogram in 1973, and only $0.30 in 1985.

The high price of eggs encourages fishermen to catch more eggs each year for the Japanese market. Although the ultimate aim is the eggs, the pakkajas require that vast amounts of fish also are caught. This increasing harvest of eggs and fish has raised concerns of overexploitation.

A second issue concerns the gill nets that Indonesian fishermen have used to catch flying fish since 1973. Although the use of gill nets is less expensive than us-
ing pakkajas, gill nets catch mostly immature flying fish—in effect, gill net fishermen forgo the opportunity to obtain fish eggs. The utilization of gill nets therefore could lower the net benefit for the flying fish fishery (Budihardjo and Nessa 1982; Dwiponggo et al. 1981; Zerner 1987).

Indonesian researchers have conducted several studies to examine these two problems of overexploitation and gill net use. Dwiponggo et al. (1981 and 1982), applying a static model of the flying fish fishery, estimated that the maximum sustainable annual yields of the flying fish and their eggs are approximately 16,000–17,000 tons and 138–150 tons, respectively.

Budihardjo and Nessa (1982) conducted a comparative study on the technical and economic aspects of catching flying fish with pakkajas and gill nets. They suggested the prohibition of gill nets during March and April, so gill net fishermen could not catch immature flying fish.

None of the above papers uses a dynamic bioeconomic model as a base for its results. However, a dynamic model that describes the biological characteristics of flying fish and the economic conditions of the fishery will produce more accurate results than a static model, and provide a year-to-year optimal harvest policy. The main difficulty in developing a dynamic bioeconomic model of the flying fish fishery is that the data on the flying fish population are very poor.

Hence, the first goal of this paper is to develop a bioeconomic model of the Indonesian flying fish using the very limited existing information about the fish population. The paper will develop several reasonable assumptions and use a calibration technique. The second goal is to determine the optimal harvest policy for the flying fish.

In addition to researchers interested in the flying fish fishery, this paper is also useful for researchers who want to develop a dynamic bioeconomic model of other fisheries where data on fish populations are very limited. This category includes most fisheries in developing countries.

The Model

Flying fish are fast-moving fish that have a habit of leaping out of the water and “flying” over long distances. Around February they migrate in a group from the north part of Sulawesi into the Makasar Straits (figure 1). They swim in the South Sulawesi area from about April through June, in concurrence with their spawning season. They then continue eastward, some to the north and others to the south to the Banda Sea (Dwiponggo et al. 1981).

The fact that the flying fish is a single cohort (Khokiattiwong 1988) which lives for only eighteen months simplifies the biological model. Define $X_t$ as the biomass level of the flying fish population at the beginning of the spawning season in year $t$. $Y_t$ is the amount of flying fish, by weight, caught by gill nets in year $t$. $H_t$ is the amount of flying fish, by weight, caught by pakkajas. $E_t$ is the amount of the eggs, by weight, caught by pakkajas. Let

$$E_t = \gamma H_t; \quad \gamma > 0$$

In year $t$, the amount of fish not caught by pakkajas and gill nets is $X_t - Y_t - H_t$. Hence, the biological model

$$X_{t+1} = T(X_t - Y_t - H_t)$$

where $T(\cdot)$ is assumed to be a strictly concave and twice differentiable function of $X_t$, $Y_t$, and $H_t$. 

Pakkajas catch the fish in their spawning period, while gill nets catch immature fish and fish in their post-spawning phase. Therefore, the fish caught by pakkajas each year are those not caught by gill nets and vice versa, i.e.

\[ Y_t = Y(X_t - H_t, N_t) \] (3)

and

\[ H_t = H(X_t - Y_t, M_t) \] (4)

where \( N_t \) is number of gill nets used to catch flying fish in year \( t \), and \( M_t \) is number of pakkajas in year \( t \).

By estimating the two equations above, the cost of operating gill nets and pakkajas can be shown as a function of the amount of fish caught by each method and the biomass of fish in the sea.

\[ CN(N_t) = CN(X_t - H_t, Y_t) \] (5)

\[ CM(M_t) = CM(X_t - Y_t, H_t) \] (6)

where \( CN(\cdot) \) is the cost of using gill nets, and \( CM(\cdot) \) is the cost of using pakkajas. The above cost functions are assumed to be perfectly malleable and strictly convex.

As mentioned earlier, Japan is the most important market for the eggs. Since Japan also imports flying fish eggs from other countries, the model applies a price-taker assumption to the price of Indonesian flying fish eggs.

In contrast, flying fish are sold only to local consumers, and the local market is
supplied only by the fish caught in South Sulawesi waters. Thus, the amount of fish caught each year dictates the price of the fish. Now, the problem of maximizing the present value of the net benefit to society from the flying fish fishery throughout an infinite time horizon can be summarized as a dynamic programming problem

$$\max_{\{Y_t, H_t\}_{t=0}} \sum_{t=0}^{\infty} \rho^t \left[ \int_{0}^{H_t + Y_t} P(h_t + y_t) d(h_t + y_t) + P_R \cdot E_t - CN(X_t - H_t, Y_t) - CM(X_t - Y_t, H_t) \right]$$

subject to

$$X_{t+1} = T(X_t - H_t - Y_t); \quad \forall t = 0, 1, \ldots$$
$$X_0 = X_{\text{init}}$$
$$X's, H's, Y's \geq 0$$

where \(P(h_t + y_t)\) is the price of the fish in year \(t\) as a linear function of the total quantity of flying fish caught in year \(t\), \(P_R\) is the price of the eggs, \(X_{\text{init}}\) is the initial level of biomass (from the data), and \(\rho\) is a discount factor.

The Search for the Biological Model

Several functions are commonly used as biological models. From these functions, choose a simple logistic growth function for the biological model of flying fish

$$X_{t+1} = A \cdot \left( X_t - H_t - Y_t \right) \left( 1 - \frac{X_t - H_t - Y_t}{B} \right) \tag{7}$$

If fish population data are available each year, an econometric technique can be used to estimate the equation (7) above. However, the data are not available.

This paper will develop a calibration method to search for the parameters \(A\) and \(B\). First, choose any number for \(A\) and \(B\). Second, simulate the relation (7) throughout several years. This paper simulates the relation (7) from 1967 to 1989. Third, yearly fish population resulting from this simulation should satisfy several constraints that represent the conditions of the flying fish fishery during the simulation years. If not, choose another \(A\) and \(B\).

Before developing the constraints for the fish population, define a restriction for parameter \(A\). If the fishing mortality is equal to zero, the biological model is defined as

$$X_{t+1} = A \cdot X_t \left( 1 - \frac{X_t}{B} \right) \tag{8}$$

Assume that the flying fish will reach a stable steady-state population. According to Leopunov’s indirect method, the relation (8) will have a stable steady-state condition, if the absolute value of \(\partial X_{t+1}/\partial X_t\) is less than one. This relationship is

$$\left| \frac{\partial X_{t+1}}{\partial X_t} \right| = \left| A - 2 \frac{AX_t}{B} \right| < 1 \tag{9}$$

Let \(X\) be the biomass level in the natural steady-state condition
The Indonesian Flying Fish: A Bioeconomic Model

Substituting (10) into (9), \( A \) should be between 1 and 3. Hence, define the first constraint such that \( A \) should be between 1 and 3.

Now define several other constraints representing the conditions of the fish population from 1967 to 1989. The second constraint is that the fish population in 1967 was the same as that in 1968. This constraint is based on the fact that fishermen started to export flying fish eggs in 1968. Before 1968 fishermen only sold the fish and their eggs to local markets. The prices were relatively low so no incentive existed for the fishermen to catch more fish or eggs. The Indonesian Directorate General of Fisheries estimated that in 1967 the amount of flying fish caught was approximately 4,100 tons (Cushing 1971). Thus, it can be assumed that several years before and up to 1968, the flying fish fishery reached a sustainable yield and fish population.

The third constraint is that from 1968 to 1974 the annual catch increased linearly. This assumption is necessary since no data on the annual fish catch during these years exist (see table 1).

\[
x = AX \left(1 - \frac{X}{B}\right)
\]

Table 1
Total Annual Catch of Flying Fish and Eggs and the Estimated Population in South Sulawesi Waters

<table>
<thead>
<tr>
<th>Year</th>
<th>Annual Fish Catch (tons)</th>
<th>Lower Bound Estimated Population (tons)</th>
<th>Upper Bound Estimated Population (tons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1967</td>
<td>4,100</td>
<td>32,481.822</td>
<td>32,481.471</td>
</tr>
<tr>
<td>1968</td>
<td>n.a.</td>
<td>32,481.822</td>
<td>32,481.471</td>
</tr>
<tr>
<td>1969</td>
<td>n.a.</td>
<td>32,481.822</td>
<td>32,481.471</td>
</tr>
<tr>
<td>1970</td>
<td>n.a.</td>
<td>32,310.390</td>
<td>32,310.189</td>
</tr>
<tr>
<td>1971</td>
<td>n.a.</td>
<td>32,000.000</td>
<td>32,000.000</td>
</tr>
<tr>
<td>1972</td>
<td>n.a.</td>
<td>31,515.236</td>
<td>31,515.483</td>
</tr>
<tr>
<td>1973</td>
<td>n.a.</td>
<td>30,794.898</td>
<td>30,795.456</td>
</tr>
<tr>
<td>1974</td>
<td>n.a.</td>
<td>29,738.953</td>
<td>29,739.922</td>
</tr>
<tr>
<td>1975</td>
<td>11,918</td>
<td>28,173.400</td>
<td>28,174.949</td>
</tr>
<tr>
<td>1976</td>
<td>14,304</td>
<td>25,768.264</td>
<td>25,770.708</td>
</tr>
<tr>
<td>1977</td>
<td>10,988</td>
<td>20,162.983</td>
<td>20,167.205</td>
</tr>
<tr>
<td>1978</td>
<td>6,453</td>
<td>16,905.470</td>
<td>16,912.707</td>
</tr>
<tr>
<td>1979</td>
<td>9,175</td>
<td>18,773.987</td>
<td>18,785.148</td>
</tr>
<tr>
<td>1980</td>
<td>8,447</td>
<td>17,538.792</td>
<td>17,556.172</td>
</tr>
<tr>
<td>1981</td>
<td>8,447</td>
<td>16,779.676</td>
<td>16,806.862</td>
</tr>
<tr>
<td>1982</td>
<td>7,642</td>
<td>15,608.571</td>
<td>15,652.063</td>
</tr>
<tr>
<td>1983</td>
<td>7,300</td>
<td>15,030.399</td>
<td>15,100.588</td>
</tr>
<tr>
<td>1984</td>
<td>7,437</td>
<td>14,649.624</td>
<td>14,763.534</td>
</tr>
<tr>
<td>1985</td>
<td>7,112</td>
<td>13,804.144</td>
<td>13,992.587</td>
</tr>
<tr>
<td>1986</td>
<td>7,006</td>
<td>12,934.604</td>
<td>12,522.437</td>
</tr>
<tr>
<td>1987</td>
<td>5,967</td>
<td>11,623.361</td>
<td>12,175.021</td>
</tr>
<tr>
<td>1988</td>
<td>5,927</td>
<td>11,145.583</td>
<td>12,108.814</td>
</tr>
<tr>
<td>1989</td>
<td>5,183</td>
<td>10,366.000</td>
<td>12,063.587</td>
</tr>
<tr>
<td>1990</td>
<td>n.a.</td>
<td>10,302.023</td>
<td>13,252.437</td>
</tr>
</tbody>
</table>

Source: Total annual catch of flying fish are from Cushing (1971) and the South Sulawesi Fishery Agency (1990).
The fourth constraint is that the flying fish population in 1971 was approximately 32,000 tons. This figure is based on estimations from several studies. Cushing (1971) measured the carbon contained in the Flores Sea. Based on Cushing’s data, Dwiponggo (1982) estimated that the total biomass level of all kinds of fish in the area was around 640,000 tons. He also estimated that flying fish constituted approximately 5% of the total fish in the area.

The fifth constraint is that the fish population in year \( t + 4 \) must be less than the population in year \( t \). Choosing a four-year difference allows the population to fluctuate during four years. This constraint is based on indications that the population of flying fish was decreasing after 1974. First, the data for annual catches from 1974 until 1989 show that the maximum annual catch occurred in 1976, and that the annual catches decreased after that year (table 1). Second, the data for catch per unit effort (CPUE) of pakkajas and gill nets (table 2) show that the catches per unit of effort for pakkajas and gill nets were almost consistently decreasing after 1979.

The sixth constraint is that the fish population which entered South Sulawesi waters in 1989 was at least twice the amount of fish caught in that year. This assumption is based on three facts. First, South Sulawesi waters constitute a relatively large area. Second, flying fish are fast-moving. Third, flying fish fishermen use relatively simple fishing technology. Hence, it would have been difficult for the fishermen to harvest more than half of the fish population in that year.

Note that the sixth constraint should be applied each year from 1967 to 1989. However, if this constraint is applied each year, the result would be that no solution to \( A \) and \( B \) could be found. Hence, this constraint is only applied in 1989, the last year of the simulation.

After defining all the constraints representing the conditions of flying fish during 1967 and 1989, the calibration process can be conducted by randomly choosing \( A \) and \( B \). Several combinations of \( A \) and \( B \) satisfy all the constraints. Thus the range of \( A \) and \( B \) should be defined. Define an upper bound process as a process to find the highest possible fish population in 1990. A lower bound process is a process to find the lowest possible fish population in 1990.

The process of searching for the parameters \( A \) and \( B \) can be converted to an optimization problem.

### Table 2
Number of Pakkajas and Gill Nets Used to Catch Flying Fish in South Sulawesi

<table>
<thead>
<tr>
<th>Year</th>
<th>Pakkaja (units)</th>
<th>CPUE of Pakkaja</th>
<th>Gill Net (units)</th>
<th>CPUE of Gill Net</th>
</tr>
</thead>
<tbody>
<tr>
<td>1979</td>
<td>2,082</td>
<td>2.2406</td>
<td>1,142</td>
<td>3.9501</td>
</tr>
<tr>
<td>1980</td>
<td>2,168</td>
<td>1.0925</td>
<td>1,161</td>
<td>5.2344</td>
</tr>
<tr>
<td>1981</td>
<td>2,684</td>
<td>1.4537</td>
<td>1,098</td>
<td>4.1415</td>
</tr>
<tr>
<td>1982</td>
<td>2,649</td>
<td>1.5225</td>
<td>1,137</td>
<td>3.1734</td>
</tr>
<tr>
<td>1983</td>
<td>1,748</td>
<td>1.8307</td>
<td>1,187</td>
<td>3.4540</td>
</tr>
<tr>
<td>1984</td>
<td>1,264</td>
<td>1.2983</td>
<td>1,155</td>
<td>5.0181</td>
</tr>
<tr>
<td>1985</td>
<td>1,340</td>
<td>1.7053</td>
<td>1,153</td>
<td>4.1855</td>
</tr>
<tr>
<td>1986</td>
<td>1,189</td>
<td>1.7165</td>
<td>1,073</td>
<td>4.6294</td>
</tr>
<tr>
<td>1987</td>
<td>916</td>
<td>1.4060</td>
<td>1,025</td>
<td>4.5639</td>
</tr>
<tr>
<td>1988</td>
<td>978</td>
<td>1.4096</td>
<td>995</td>
<td>4.5736</td>
</tr>
<tr>
<td>1989</td>
<td>700</td>
<td>1.5000</td>
<td>1,045</td>
<td>3.9550</td>
</tr>
</tbody>
</table>

Source: South Sulawesi Fishery Agency (1990).
max(min) $X_{1990}$, for upper bound (lower bound) \hspace{1cm} (11)

subject to

$$X_{t+1} = [A \cdot (X_t - H_t - Y_t)] \cdot \left(1 - \frac{X_t - H_t - Y_t}{B}\right), \forall t = 1967...1989$$

$$X_{1967} = X_{1968}$$

$$X_t \geq X_{t+4}, \forall t = 1967...1985$$

$$X_{1989} \geq 2H_{1989}$$

$H$’s are given and $X$’s, $A$, $B \geq 0$

Note that to have a natural steady-state condition (without fishing mortality), the first constraint should not be binding.

GAMS\MINOS optimization software is used to solve the above problem. The result for the upper bound is that $A$ equals 2.176 and $B$ equals 59,864.152. The result for the lower bound is that $A$ equals 2.176 and $B$ equals 59,869.212. It can be seen that $A$ is relatively stable at 2.176, while the range of $B$ varies from 59,864.152 to 59,869.212.

Figure 2 shows the estimated flying fish population from 1967 to 1990 resulting from the two optimizations above (see also table 1). Finally, the biomass ratio between eggs and fish caught ($\gamma$) in equation (1) above is based on the work by Nessa (1978). He estimated that the biomass ratio between eggs and fish caught by pakkajas was 1 to 10.

![Figure 2. Upper and Lower Bound Estimated Fish Population](image-url)
Estimation of the Cost and Benefit Functions

The ideal way to estimate cost and benefit functions is by simultaneously estimating the supply and demand curves. This technique requires a rigorous mathematical application to overcome the problems caused by multiple markets and nonlinear functions. Hence, each function will be estimated separately, although this method might generate less accurate estimations.

To find the cost functions, equations (3) and (4) should be estimated first. One problem in estimating these relations is the unavailability of data on flying fish caught separately by pakkajas and gill nets. Instead, data exist on the total quantity of fish caught using both types of equipment collectively. Data are also available on the quantity of eggs harvested using pakkajas. A second problem is that, for gill nets, the only data available are the total number of gill nets used each year. This number does not represent the real effort of gill nets in the flying fish fishery, since gill nets are used to catch other fish besides flying fish. To overcome the first problem, this paper uses the data on the eggs and the ratio between fish and eggs caught with pakkajas estimated by Nessa (1978). Thus the quantity of fish caught by pakkajas can be estimated. For the second problem, this study uses an estimate of around 15% of the total quantity of gill nets used each year to catch flying fish (Budihardjo and Nessa 1982), as in table 2.

This paper uses exponential production functions to represent relations (3) and (4) since the reduced forms of these functions are simple and easy to estimate. The functions are as follows

$$Y_t = (X_t - H_t) \left(1 - e^{-q_N N_t}\right)$$

and

$$H_t = (X_t - Y_t) \left(1 - e^{-q_M M_t}\right)$$

Appendix A describes the procedure and results of estimating equations (12) and (13).

Budihardjo and Nessa (1982) estimated that the annual costs for a unit of pakkaja and for a unit of gill net are around Rp. 1,510,435 and Rp. 1,110,305, respectively. Hence, the total cost functions for pakkajas and gill nets, respectively, can be shown as below

$$CN_t = 1,110,305 \cdot N_t$$

$$CM_t = 1,510,435 \cdot M_t$$

Substituting (12) into (14) and (13) into (15) produces

$$CN_t = \frac{1,110,305}{q_N} \ln \left( \frac{X_t - H_t}{X_t - H_t - Y_t} \right)$$

and

$$CM_t = \frac{1,510,435}{q_M} \ln \left( \frac{X_t - Y_t}{X_t - Y_t - H_t} \right)$$

The next step is to find the benefit function. The price of eggs is assumed constant at Rp. 10,500 per kilogram of eggs (Zerner 1987), while the price of the fish is assumed to be a function of the total amount of flying fish caught and the welfare of the people in South Sulawesi (an inverse demand function). The variables used to
represent the welfare of people in South Sulawesi are the Indonesian GNP and the total Indonesian population (table 3).

After estimating the inverse demand function (see appendix B), assume that GNP is constant at 102,000 billion rupiahs and the population of Indonesia is constant at 170 million people. The final result is

$$P_t = \alpha + \beta(H_t + Y_t)$$ (18)

where $\alpha = 429,710$, and $\beta = -17.441$

The benefit function that describes the total benefits to society from the fish and their eggs is

$$B_t = \int_0^{H_t+Y_t} [\alpha + \beta(h_t + y_t)]d(h_t + y_t) + 0.1P_RH_t$$ (19)

where $P_R = 10,500,000$ (Rp/ton), and 0.1 = the average ratio between the amount of the eggs harvested and fish caught with a unit of pakkaja.

**Optimal Management**

In this section, the paper substitutes the estimated forms of the cost, benefit, and biological functions in the previous sections into the maximization problem in the bioeconomic model. This model can be written as

$$\max \sum_{(Y_t, H_t)} \rho^t \left[ \int_0^{H_t+Y_t} [\alpha + \beta(h_t + y_t)]d(h_t + y_t) + 0.1P_RH_t \right]$$ (20)

Table 3

<table>
<thead>
<tr>
<th>Year</th>
<th>Price of Flying Fish (Rp per kg)</th>
<th>Indonesian GNP (Rp 10^9)</th>
<th>Indonesian Population (10^6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1975</td>
<td>112.82</td>
<td>12,087</td>
<td>135.67</td>
</tr>
<tr>
<td>1976</td>
<td>129.09</td>
<td>15,035</td>
<td>133.53</td>
</tr>
<tr>
<td>1977</td>
<td>151.87</td>
<td>18,332</td>
<td>136.63</td>
</tr>
<tr>
<td>1978</td>
<td>256.96</td>
<td>21,854</td>
<td>139.80</td>
</tr>
<tr>
<td>1979</td>
<td>255.13</td>
<td>30,541</td>
<td>143.04</td>
</tr>
<tr>
<td>1980</td>
<td>247.49</td>
<td>43,435</td>
<td>147.49</td>
</tr>
<tr>
<td>1981</td>
<td>232.75</td>
<td>56,197</td>
<td>151.31</td>
</tr>
<tr>
<td>1982</td>
<td>228.81</td>
<td>60,496</td>
<td>154.66</td>
</tr>
<tr>
<td>1983</td>
<td>294.68</td>
<td>74,396</td>
<td>158.08</td>
</tr>
<tr>
<td>1984</td>
<td>255.81</td>
<td>85,569</td>
<td>161.58</td>
</tr>
<tr>
<td>1985</td>
<td>316.45</td>
<td>92,909</td>
<td>164.05</td>
</tr>
<tr>
<td>1986</td>
<td>324.78</td>
<td>98,320</td>
<td>168.35</td>
</tr>
</tbody>
</table>

subject to

\[ X_{t+1} = A(X_t - H_t - Y_t) \left( 1 - \frac{X_t - H_t - Y_t}{B} \right), \quad \forall t = 0, 1, \ldots, \infty \]

\[ X_0 = X_{1990} \]

where \( \rho = 0.89 \) since the discount rate is assumed to be approximately 12\% per year.

The estimated fish population in 1990 is used as the initial condition. The maximization problem above is solved using GAMS/MINOS optimization software. Appendix C outlines the detailed procedure used to solve the problem (20) above. Figure 3 shows the optimal harvest policy during the thirteen-year time horizon. No gill net is allowed to catch flying fish during the spawning season in South Sulawesi waters, and a year’s delay in harvesting the fish is suggested. The present values of the total net benefit from the flying fish fishery throughout the thirteen-year time horizon are 58 billion rupiahs and 59 billion rupiahs, using the lower and the upper bound fish population data, respectively.

The two optimal harvest policies in figure 3 can be interpreted as a range of the optimal harvest. Figure 4 shows the optimal path of the fish population. In both scenarios, the fish population is expected to be in a steady-state condition by year ten.

Figure 5 shows the optimal harvest policies if the discount factor (\( \rho \)) equals 0.81 and 1, or the discount rate is assumed to be approximately 24\% and 0\%, respectively. It can be seen that the suggestions to implement a one-year delay in harvesting the fish and to ban the use of gill nets are relatively stable.
Discussion

This paper shows that a calibration method can be used to build a dynamic biological model when population data are very limited. This paper also demonstrates the procedure to determine the annual optimal harvest amount of flying fish and their eggs. With a dynamic model, it can be seen how long and by how much people should reduce their harvest so that they can enjoy a larger net benefit from the fishery. This information cannot be found in a static model.

Two important points deserve mention in using the calibration method in this paper. The first point is the choice of the functional form to represent the biological model. One should apply several functional forms and observe the estimated fish population and the projected optimal management policy resulting from each functional form. From the estimated population and the projected optimal policy, one should decide which functional form(s) is (are) reasonable. For example, in the case of Indonesian flying fish, one should eliminate any functional form which estimates a relatively steady fish population from 1967 to 1989. One should also eliminate any functional form which projects an extremely high net benefit from the fishery. This paper used a logistic function since other functions\(^1\) were not be able to generate results for \(A\) and \(B\) in the optimization problem (11).

The second point is the constraint assumptions. If the constraints reflect the real world, then it can be argued that the results from the calibration should be close to

\(^1\) \(X_{t+1} = A + BX_t\), and \(X_{t+1} = A X_t^p\)
the results from the true relationships. Imposing constraints that are too strong, however, can create an unreasonable solution. The same situation might occur if the constraints are too weak. For example, if the fourth constraint in the optimization problem (11) is $X_t \geq X_{t+1}$, no solution exists for that problem. Omitting this fourth constraint could result in a steady fish population from 1967 to 1989.

The optimal solution resulting from the bioeconomic model in this paper suggests delaying the harvest of the fish and their eggs for one year and, after that year, slowly increasing the quantity harvested. This paper also recommends that fishermen do not use gill nets during the spawning season. In interpreting the latter recommendation, one should remember two points. The first point is the assumption in this model that gill nets catch pre-spawning fish if they are used during the spawning season. The second point is that flying fish are a single cohort. Post-spawning fish will not return next year during the spawning season. Therefore, the correct interpretation of the results in this paper is that gill nets should not be used to catch pre-spawning fish, but they should (could) be used to catch post-spawning fish. In practical terms, fishermen should use gill nets after the spawning season in the eastern part of South Sulawesi waters. One should also note that since pakkajas cannot be used to catch post-spawning fish, gill nets are the only tool to catch these fish.

The benefit of having post-spawning fish in the sea is essentially zero in this model, i.e. post-spawning fish contribute nothing to next year’s new recruitment process. Hence, the optimal amount of post-spawning fish caught by gill nets occurs where the marginal cost of catching that last unit of fish equals the price of that unit of fish.

The optimal solution, however, should be appropriately qualified. First, the model does not take into account the possibility that stopping the harvest for one

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{optimal_harvest_policy.png}
\caption{Optimal Harvest Policy When $\rho$ Equals 0.81 and 1 (no gill net is allowed to catch flying fish during the spawning season)}
\end{figure}
year might adversely affect the established marketing and distribution infrastructure. To avoid this potentially negative impact, one could add another constraint to the bioeconomic model—not to reduce the harvest more than, for example, 50% or 67% from the previous year's harvest. Second, the model assumes that there are no technological improvements in fishing in the future time. This strong assumption is made because developing a model with uncertainty about future conditions is very difficult. Hence, it is recommended to recalculate the model as significant new information occurs. Third, the model does not take into account the possibility that implementing the optimal solution might induce an undesirable redistribution of income between pakkaja fishermen and gill net fishermen. Specifically, while this optimal solution benefits pakkaja fishermen, it might adversely affect the incomes of gill net fishermen; under the optimal solution, no gill net is allowed to catch flying fish during the spawning season. Thus, who can use the pakkaja and who can only use the gill net is a critical issue. Although this issue beyond the scope of this paper, it certainly should be addressed in the future.

In the Indonesian flying fish fishery, policy recommendations to address resource exploitation issues are difficult to determine. When an urgent need exists for such a recommendation, the results from the calibration method and model presented in this paper can be of value.

Appendix A. Estimation of the Production Function

Using an exponential production function, the relationships between catch and effort in the flying fish fishery are

\[ Y_t = (X_t - H_t)(1 - e^{-q_N N_t}) \]  
\[ H_t = (X_t - Y_t)(1 - e^{-q_M M_t}) \]

To find the reduced form, manipulate (A1) and (A2) to become

\[ \frac{Y_t + H_t - X_t}{X_t - H_t} = -e^{-q_N N_t} \]  
\[ \frac{H_t + Y_t - X_t}{X_t - Y_t} = -e^{-q_M M_t} \]

Then, divide (A4) by (A3)

\[ \ln \left( \frac{X_t - H_t}{X_t - Y_t} \right) = -q_M M_t + q_N N_t \]

The results of estimating the relation (A5) are:

1. Using the lower bound data for fish population
\[
\ln \left( \frac{X_t - H_t}{X_t - Y_t} \right) = -0.000235M_t + 0.000546N_t
\]

\[R^2 = 0.69 \quad \text{D-W statistics} = 2.09\]

2. Using the upper bound data for fish population

\[
\ln \left( \frac{X_t - H_t}{X_t - Y_t} \right) = -0.0000210M_t + 0.000498N_t
\]

\[R^2 = 0.65 \quad \text{D-W statistics} = 2.22\]

where \(R^2\) is not a valid measure of fit when the intercept is suppressed.

The Cobb-Douglas production function is not chosen in this paper since it cannot provide a reduced form that is both easy to estimate and give the coefficients of the original formulas.

**Appendix B. Estimation of the Benefit Function**

A linear inverse demand function is chosen in this paper. The main reasons for choosing the linear function is that it is very simple. A simple formula is needed to reduce the complexity of the dynamic optimization problem as in equation (20).

The result of the estimation is

\[P_t = 338,948 - 17.441(Y_t + H_t) + 0.15127 \frac{\text{GNP}}{\text{CAPITA}}\]

\[R^2 = 0.86 \quad \text{D-W statistics} = 2.10\]

**Appendix C. Optimal Management of Flying Fish**

The Lagrangian formulation of the dynamic optimization problem (20) is

\[L = \sum_{t=0}^{\infty} \rho^t \left( \frac{u_t + \gamma_t}{1 - \rho} - \beta(h_t + y_t)d(h_t + y_t) + 0.1P_RH_t - \frac{1,510,435}{q_M} \ln \frac{X_t - Y_t}{X_t - Y_t - H_t} \right) \]

\[- \frac{1,110,305}{q_N} \ln \frac{X_t - H_t}{X_t - H_t - Y_t} + \rho \lambda_{t+1}\left( A(X_t - H_t - Y_t)\left(1 - \frac{X_t - H_t - Y_t}{B}\right) - X_{t+1}\right) \]

\[+ \gamma_0(X_{1990} - X_0)\]

The Kuhn-Tucker first-order necessary conditions are

\[\frac{\partial L}{\partial X_t} = \frac{1,510,435}{q_M} \frac{H_t^*}{(X_t^* - Y_t^*)(X_t^* - Y_t^* - H_t^*)} + \frac{1,110,305}{q_N} \frac{Y_t^*}{(X_t^* - H_t^*)(X_t^* - H_t^* - Y_t^*)}\]
Note that the objective function (20) and all the constraints are strictly concave and twice differentiable functions of $X_t$, $Y_t$, and $H_t$. The first step in solving the problem above is to find the long-run optimal steady-state condition. In this condition, the annual biomass in the sea and the annual quantity of fish caught are the same. Hence, the optimal long-run steady-state condition can be found by dropping the
time notation \((t)\) in equations (C2)-(C9) and then solving those relations. The second step is to change the time horizon to a finite time horizon \(T\). An additional constraint that must be added is that in year \(T\) the population is already at the steady-state condition. Then solve the equations (C2)-(C9) for the \(T\)-year time horizon. If the fish population is already stable at the steady-state condition several years before year \(T\), this path is the solution to problem (20). However, if the population has not reached the steady-state condition in year \(T - 1\), increase \(T\).

References


